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EVALUATION OF SOLAR PHOTOVOLTAIC ARRAYS FOR USE ON MARINE AIDS --ETC(U)
MAR 79 R K KOSTUK
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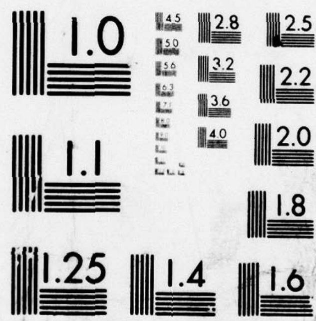

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

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16. Abstract

During the period from May 1974 to July 1978, four test and evaluation programs of solar photovoltaic arrays were conducted to evaluate the potential of these energy sources for use on marine aids to navigation. Array testing consisted of: (1) long-term rooftop exposure; (2) field deployment on buoys in Alaska, Florida, and Massachusetts; (3) field deployment on buoys in Long Island Sound; and (4) initial development of a screening test to evaluate performance in a short time frame. The results of these tests are presented.

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METRIC CONVERSION FACTORS

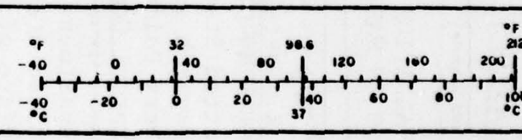
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

In 1972 the Coast Guard began an investigation of alternative energy sources which might serve as a replacement for air-depolarized batteries operating on fixed and floating lighted aids to navigation.

Specific energy sources studied were solar photovoltaic arrays, fuel cells, and wave-activated turbine generators. From these, solar photovoltaic energy systems emerged as the source most likely to satisfy the various energy requirements of the Coast Guard's lighted aids to navigation.

Little information existed at that time on the long-term operation of solar photovoltaic energy systems in a marine environment. Therefore, it was decided to test and evaluate sample systems in environments similar to those in which aids to navigation operate.

The initial emphasis of the test program was placed on evaluating the operation of complete systems (i.e., a storage battery with voltage regulator and a compatible photovoltaic array). Four test and evaluation programs were performed between May 1974 and July 1978 for system evaluation:

1. Natural exposure of arrays on a rooftop facility located at Avery Point, Groton, Connecticut.
2. Field deployment of solar arrays on buoys at Ketchikan, Alaska; St. Petersburg, Florida; and Boston, Massachusetts.
3. Field deployment of solar arrays on buoys in Long Island Sound at a location near Avery Point, Groton, Connecticut.
4. Initial development of a screening test intended for evaluating the performance of solar photovoltaic arrays in a short time frame.

In November 1977 the emphasis of the Coast Guard's solar energy investigations was changed to the separate analysis of solar arrays and storage batteries. In this report, existing data from the early test and evaluation programs, which can be used to aid the present studies of solar arrays, is considered and the results summarized.

2.0 ROOFTOP TESTS

The rooftop test was conducted to evaluate long-term solar photovoltaic energy system operation in a coastal environment. In regard to photovoltaic operation, this evaluation consisted of monitoring the total array current output at two voltage points as a function of time.[1]

Fifty-three silicon solar photovoltaic arrays were placed in operation during May 1974. Twenty-eight were obtained from Heliotek, Model LECA PN060015 (this manufacturer has since been incorporated by Spectrolab), and twenty-five from Centralab Semiconductor, Model D-805457 (this manufacturer has since been incorporated into OCLI). In October 1977, five Spectrolab Model L 12.5 and five E-Series Solar Power panels were added to the evaluation.

Panels used in the rooftop test were placed into the energy-conversion systems depicted diagrammatically in Figure 2.1.

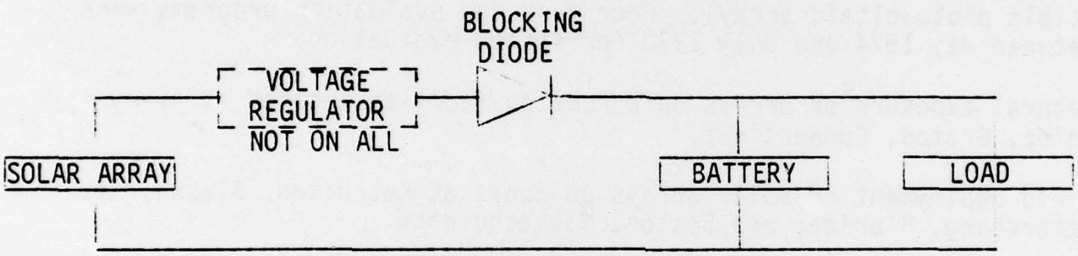

FIGURE 2.1

SOLAR PHOTOVOLTAIC ENERGY SYSTEMS EMPLOYED IN ROOFTOP TEST

The rooftop test facility is located at the north end of a roof on a two-story building at Avery Point, Groton, Connecticut (Figure 2.2). The view to the east is clear to the horizon, while the view to the south and west is clear to an elevation of about 15°. The north view is obstructed from the horizon to an elevation of 30°-35°. In the figure, all of the solar arrays are on the left side and the associated weatherproof boxes holding the storage batteries, voltage regulators, and other circuitry is on the right. The arrays are mounted horizontally. Output cabling from all boxes lead to a room one floor below the roof where the system loads and data-collection equipment are located. The building is located about 200 meters from the waters of Fisher's Island Sound, at latitude 41°19'N, longitude 72°04'W.

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[1]Results obtained from system testing for components other than the solar photovoltaic arrays will be presented in separate reports.

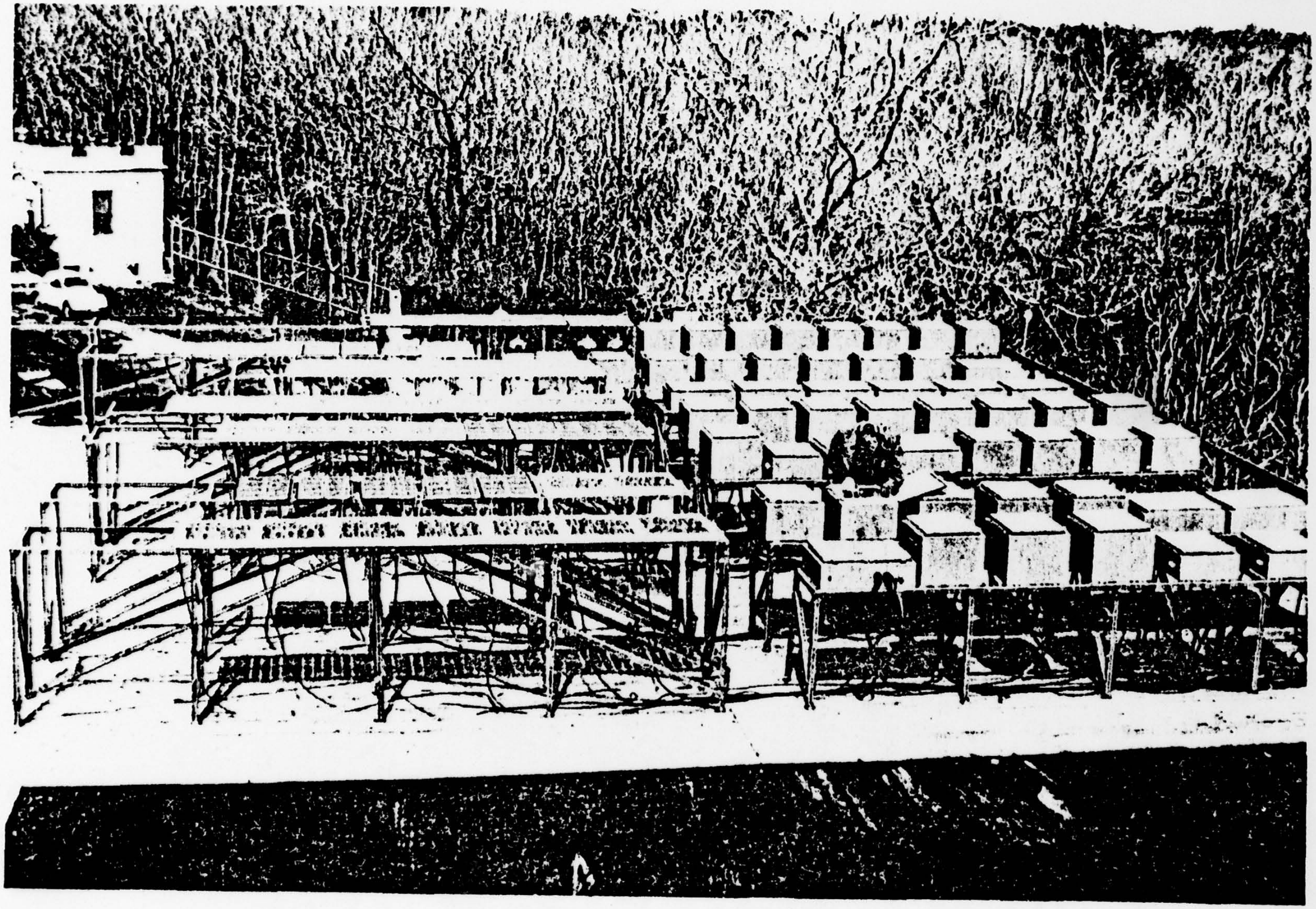

FIGURE 2.2. ROOFTOP FACILITY AT AVERY POINT, NORTH VIEW

The current output data of the arrays were normalized to an irradiance level of 100 mw/cm^2 at 25^{o}C and monitored with the terminal voltage at 0.0V and 13.5V. These voltages were maintained by shorting and resistively loading the output terminals. Measurements are summarized in Tables 2.1 and 2.2 and Figures 2.3 through 2.10. The current data presented is given as "percent of new" values which are expressed relative to the initial current output data provided by the manufacturers.

Twenty-two of the Spectrolab arrays were removed from the test after fifteen months of exposure. This was done because the output of these arrays fell below 60 percent of their new output. Examination of these arrays revealed that many of the interconnects between cells had parted, but the encapsulant remained intact. The six remaining Spectrolab arrays continue to function with an output power similar to that from the OCLI group.

The data was analyzed using the t-statistic and student's t distribution to test certain hypotheses:

The first hypothesis was that there is no significant difference in performance between arrays from different manufacturers. The analysis showed that after 15 months of exposure, this hypothesis was not rejected at the 95% confidence level (C.L.), when comparing the OCLI (D-805457) and Spectrolab (L12.5) arrays, or when comparing the Solar Power (E Series) and Spectralab (LECA PN060015) arrays. The hypothesis is rejected, however, when comparing either of the former with either of the latter. This implies that the OCLI (D-805457) and the Spectrolab (L12.5) performed significantly better than the Solar Power (E-Series) and the Spectrolab (LECA PN060015). Other differences were insignificant at the 95% C.L.

A comparison of the OCLI (D-805457) and the Spectrolab (LECA PN060015) arrays surviving 50 months of exposure, does not reject this hypothesis at the 95% C.L. This implies that the performance of the surviving arrays from each manufacturer were not significantly different. It should be noted, however, that twenty-four (96%) of the OCLI arrays survived the 50 month exposure test while only six (21%) Spectrolab arrays survived the same period.

The second hypothesis tested was that there is no significant change in performance as a function of exposure time. A comparison of output data at the 15 and 50 month exposure points rejected this hypothesis at the 95% C.L., implying that a significant decrease in performance does occur with increasing exposure time.

TABLE 2.1

CURRENT OUTPUT VERSUS EXPOSURE TIME FOR ARRAYS IN ROOFTOP TEST

MANUFACTURER (VOLTAGE)†		EXPOSURE TIME (MONTHS FROM START OF TEST) 0	5	8	11	13	15	16[x]	17	18	22	26	28	41	50
S* 0.0V	$\bar{x}$ =	100[a]	77	83	79	67	68	102	94	98	97	93	94	93	90
	S =	N.A.	22	14	19	21	22	3	15	4	2	5	5	6	8
	N =	28	27	28	28	27	27	6	6	6	5	6	6	5	5
S* 13.5V	$\bar{x}$ =	100	73	78	78	64	65	98	91	96	94	93	93	92	85
	S =	N.A.	22	16	20	22	23	5	14	3	5	4	4	6	8
	N =	28	27	28	25	27	27	6	6	6	5	6	6	5	5
O$ 0.0V	$\bar{x}$ =	100	96	91	94	92	93	97	98	99	97	94	94	92	89
	S =	N.A.	4	5	4	4	4	4	4	3	4	4	4	5	10
	N =	25	23	25	25	24	23	25	22	22	21	20	20	24	24
O$ 13.5V	$\bar{x}$ =	100	94	90	93	89	91	94	92	96	95	91	91	90	85
	S =	N.A.	4	5	4	4	4	4	5	5	4	5	5	7	10
	N =	25	23	25	17	25	23	25	22	22	21	20	20	24	24

†Terminal voltage when current was monitored
*Spectrolab (Heliokek) Model LECA PN060015
$OCLI (Centrolab Semiconductor) Model D-805457
[x]Most Spectrolab panels removed from test because their current output fell below 60 percent of their new current output values.

[a]Current output after exposure on roof expressed as a percentage relative to the panel output when new.

N = Number of photovoltaic arrays

$$\bar{x} = \sum_{i=1}^{N} x_i/N \quad \text{where } x_i = \frac{\text{Current Output At Particular Month For One Array}}{\text{Average Current Output For Particular Model Array When New}}$$

$$S = \left[\frac{\sum_{i=1}^{N}(x_i - \bar{x})}{(N-1)}\right]^{1/2}$$

TABLE 2.2

NORMALIZED CURRENT OUTPUT VERSUS EXPOSURE TIME

MANUFACTURER VOLTAGE	EXPOSURE TIME (MONTHS FROM START OF TEST)			
		0	7	15
Spectrolab	$\bar{x}$ =	100	99	91
(Model L 12.5)	σ =	0	1	2
0.0V	N =	5	5	5
Spectrolab	$\bar{x}$ =	100	99	91
(Model L 12.5)	σ =	0	1	3
13.5V	N =	5	5	5
Solar Power	$\bar{x}$ =	100	89	76
(E-Series)	σ =	0	1	2
0.0V	N =	5	5	5
Solar Power	$\bar{x}$ =	100	87	76
(E-Series)	σ =	0	1	9
13.5V	N =	5	5	5

Current output after exposure on the roof
expressed as a percentage relative to the panel output when new.

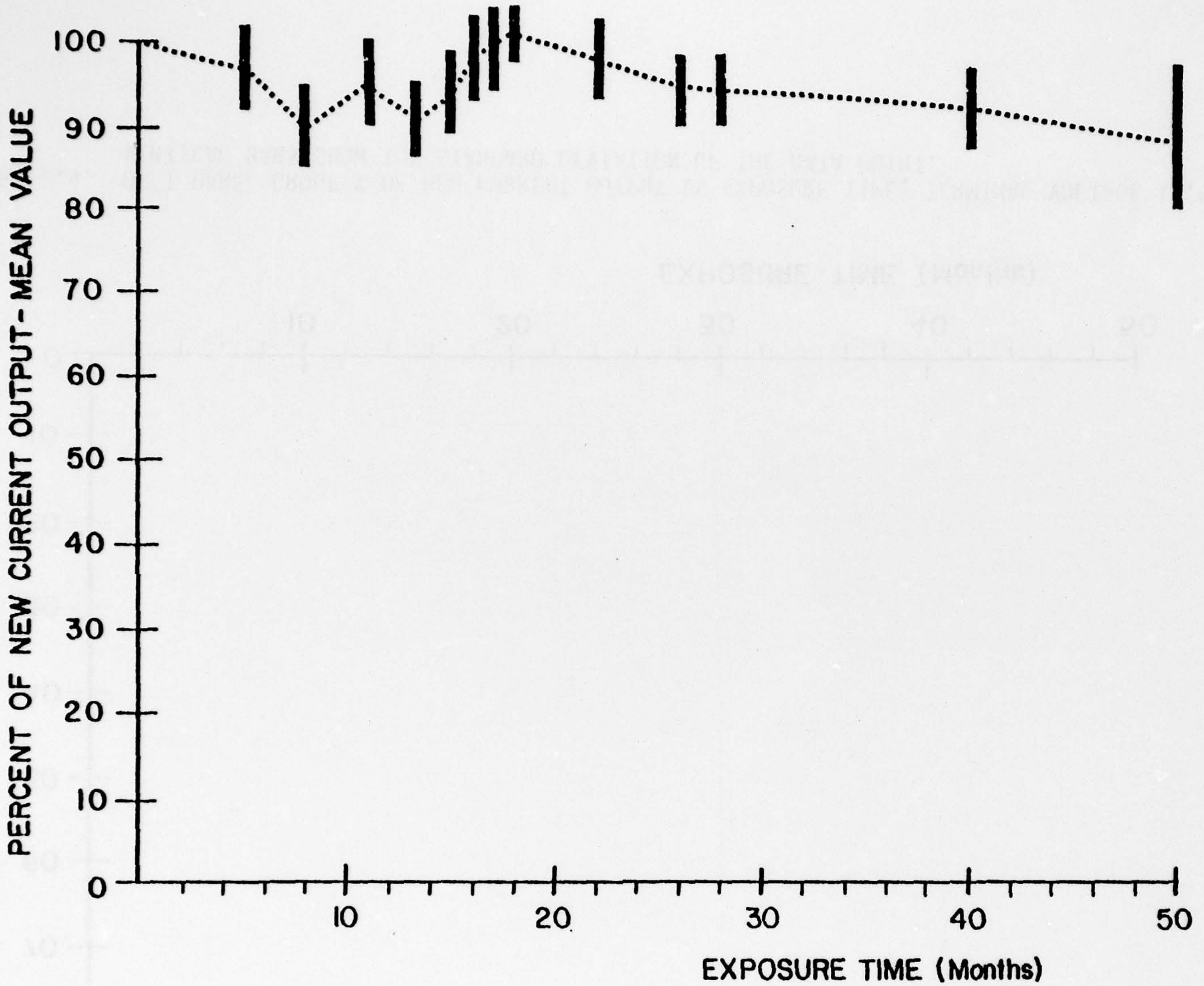

FIGURE 2.3. OCLI PANEL GROUP % OF NEW CURRENT OUTPUT VS EXPOSURE TIME; TERMINAL VOLTAGE 0.0V. VERTICAL BARS SHOW THE STANDARD DEVIATION OF THE DATA POINT.

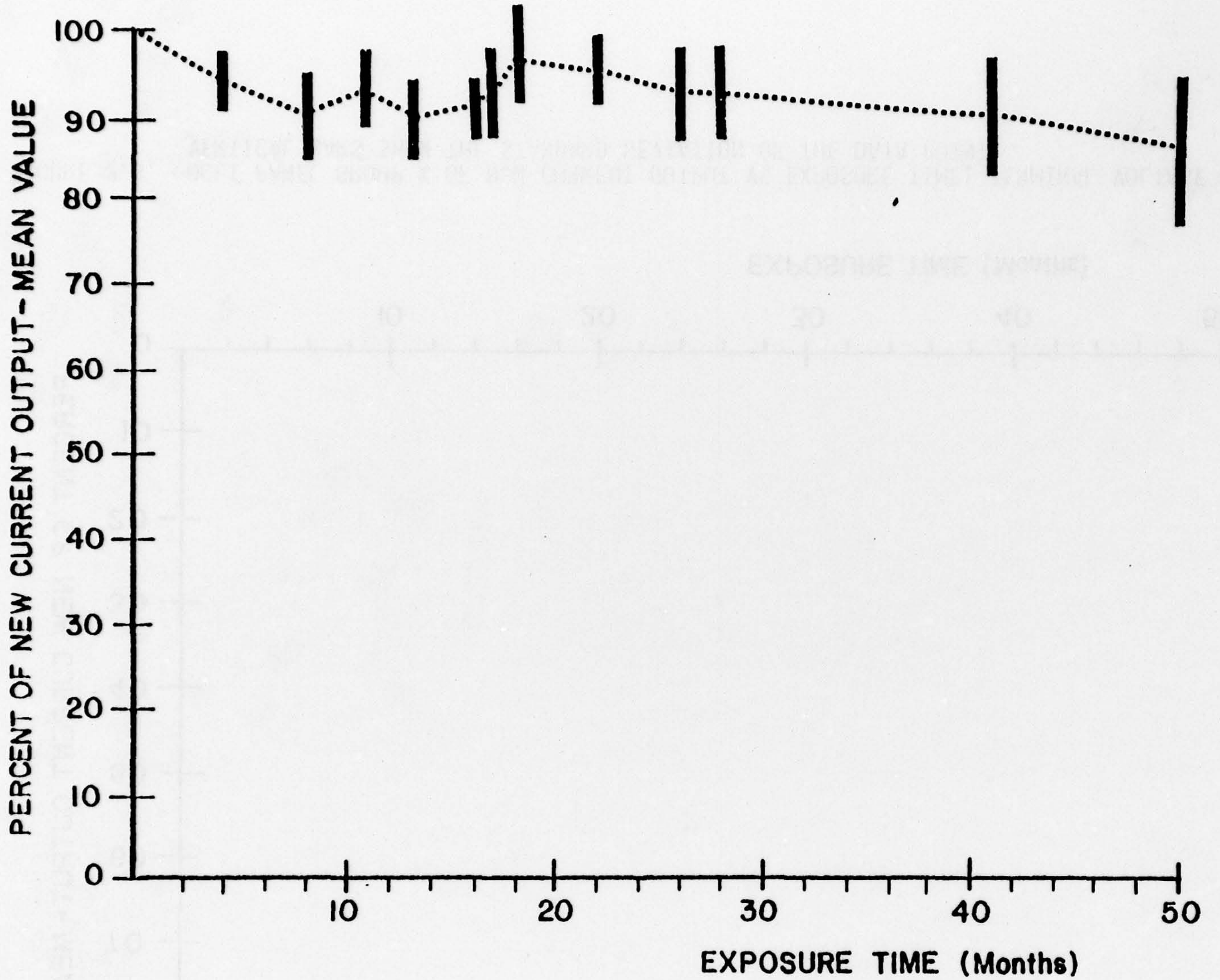

FIGURE 2.4. OCLI PANEL GROUP % OF NEW CURRENT OUTPUT VS EXPOSURE TIME; TERMINAL VOLTAGE 13.5V. VERTICAL BARS SHOW THE STANDARD DEVIATION OF THE DATA POINT.

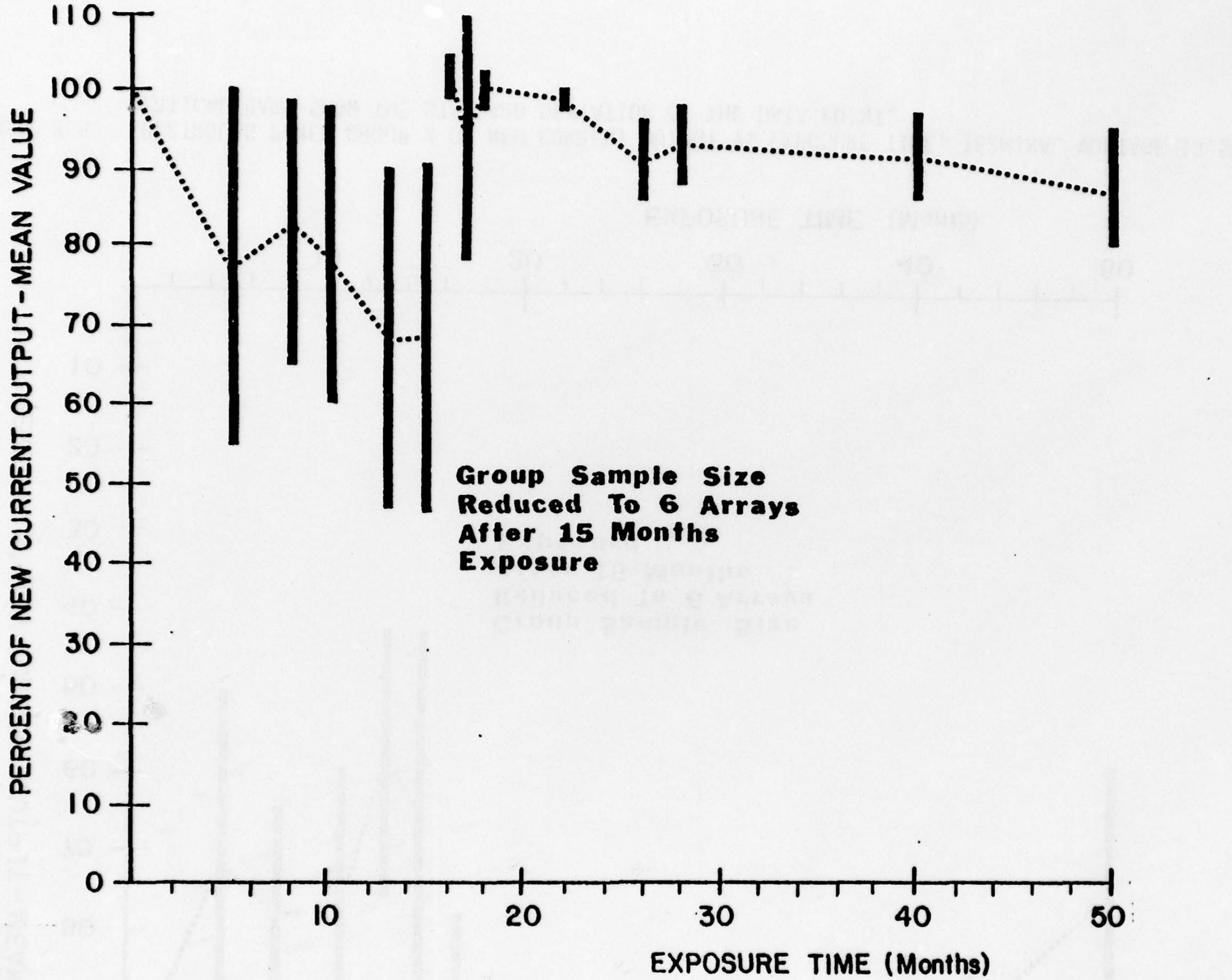

FIGURE 2.5. SPECTROLAB PANEL GROUP % OF NEW CURRENT OUTPUT VS EXPOSURE TIME; TERMINAL VOLTAGE 0.0V. VERTICAL BARS SHOW THE STANDARD DEVIATION OF THE DATA POINT.

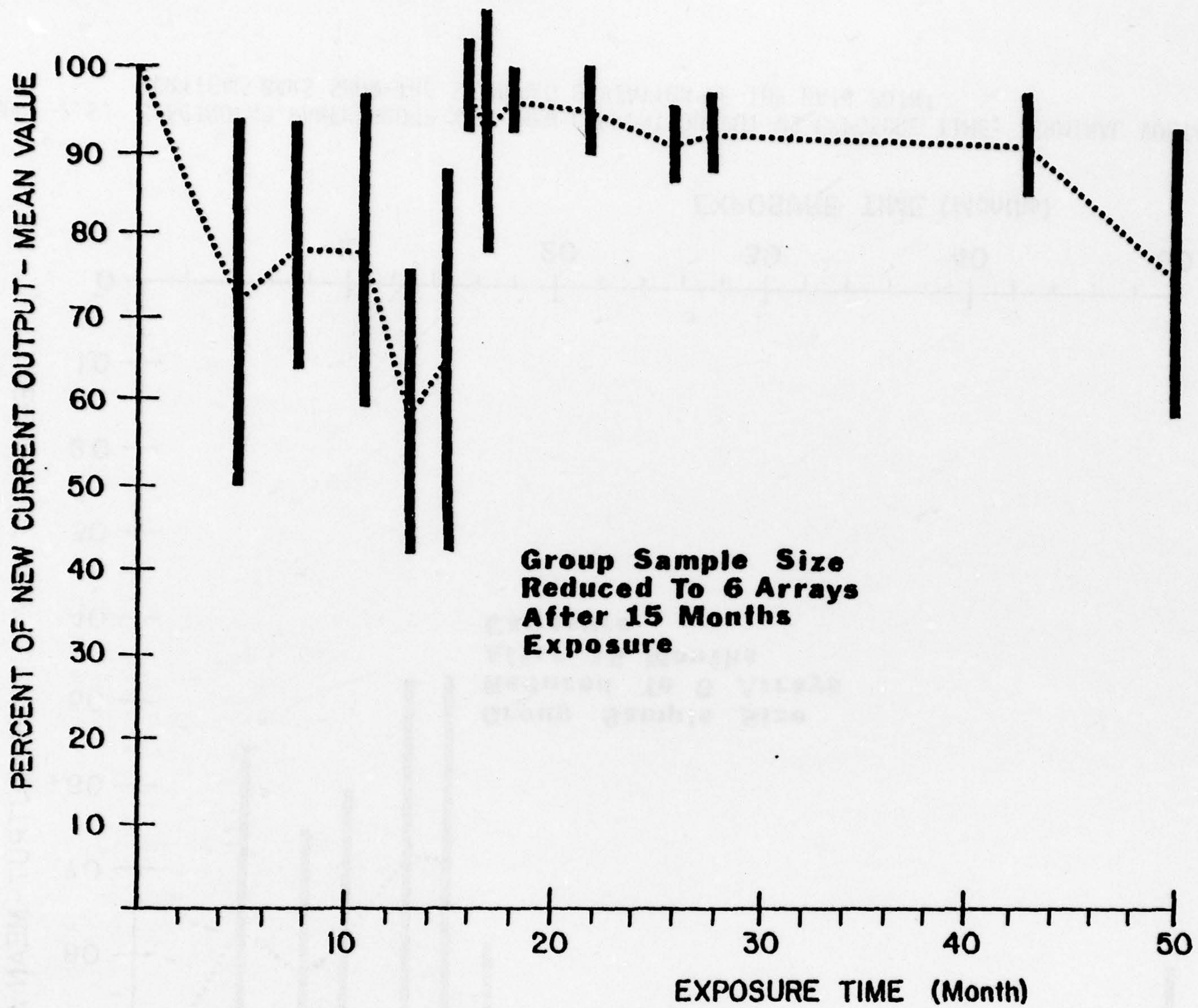

FIGURE 2.6. SPECTROLAB PANEL GROUP % OF NEW CURRENT OUTPUT VS EXPOSURE TIME; TERMINAL VOLTAGE 13.5V. VERTICAL BARS SHOW THE STANDARD DEVIATION OF THE DATA POINT.

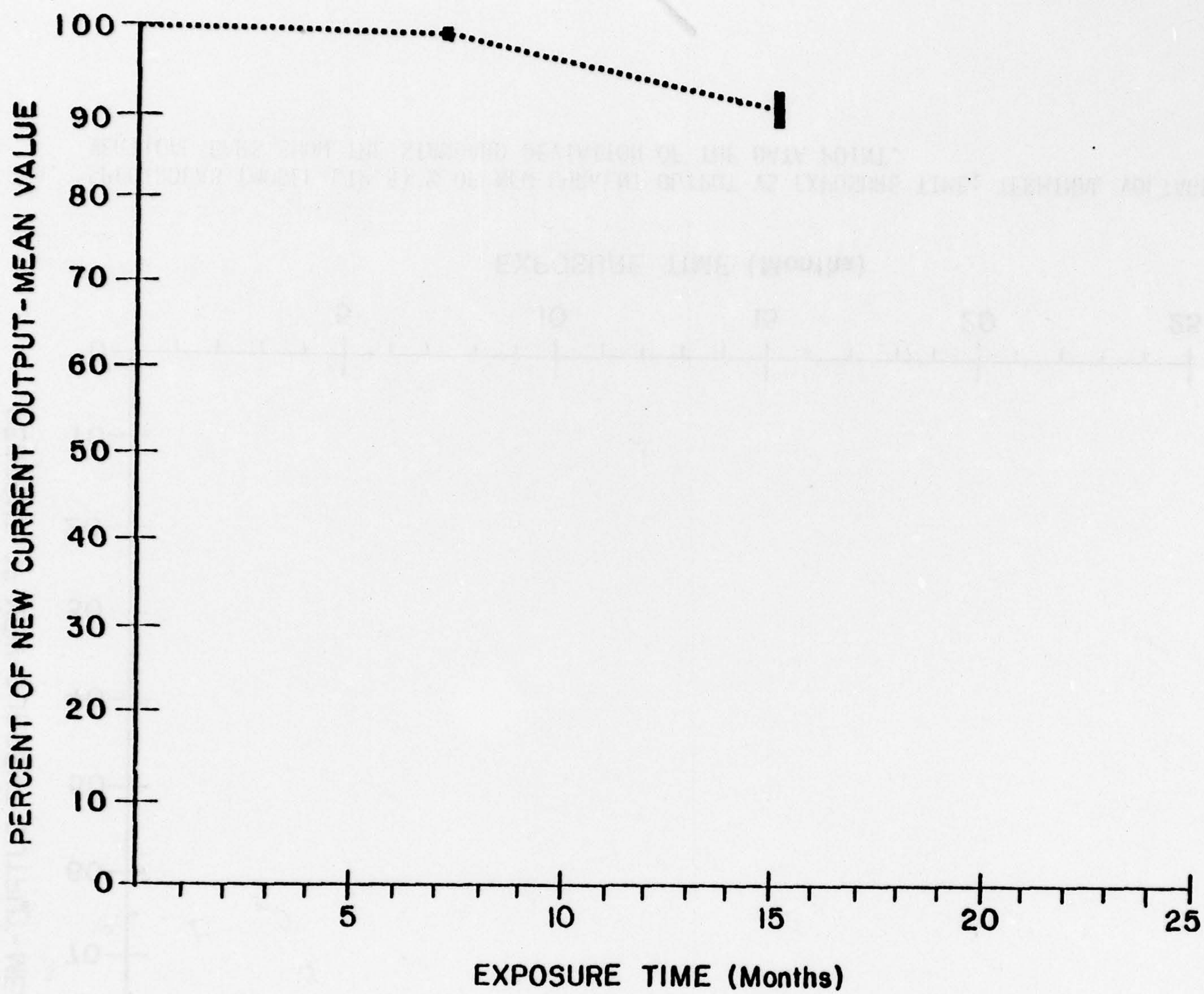

FIGURE 2.7. SPECTROLAB (MODEL L12.5) % OF NEW CURRENT OUTPUT VS EXPOSURE TIME; TERMINAL VOLTAGE 0.0V. VERTICAL BARS SHOW THE STANDARD DEVIATION OF THE DATA POINT.

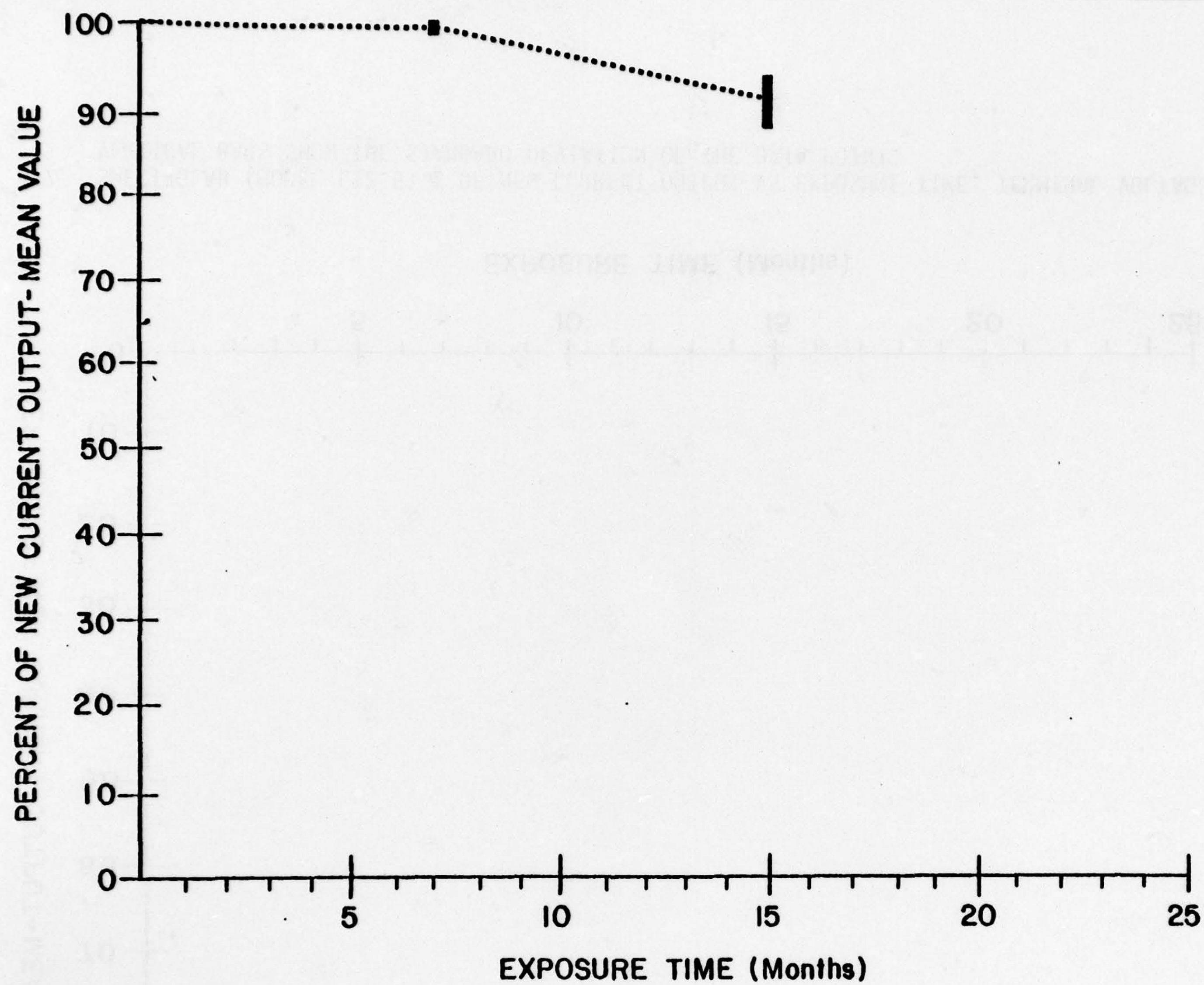

FIGURE 2.8. SPECTROLAB (MODEL L12.5) % OF NEW CURRENT OUTPUT VS EXPOSURE TIME; TERMINAL VOLTAGE 13.5V. VERTICAL BARS SHOW THE STANDARD DEVIATION OF THE DATA POINT.

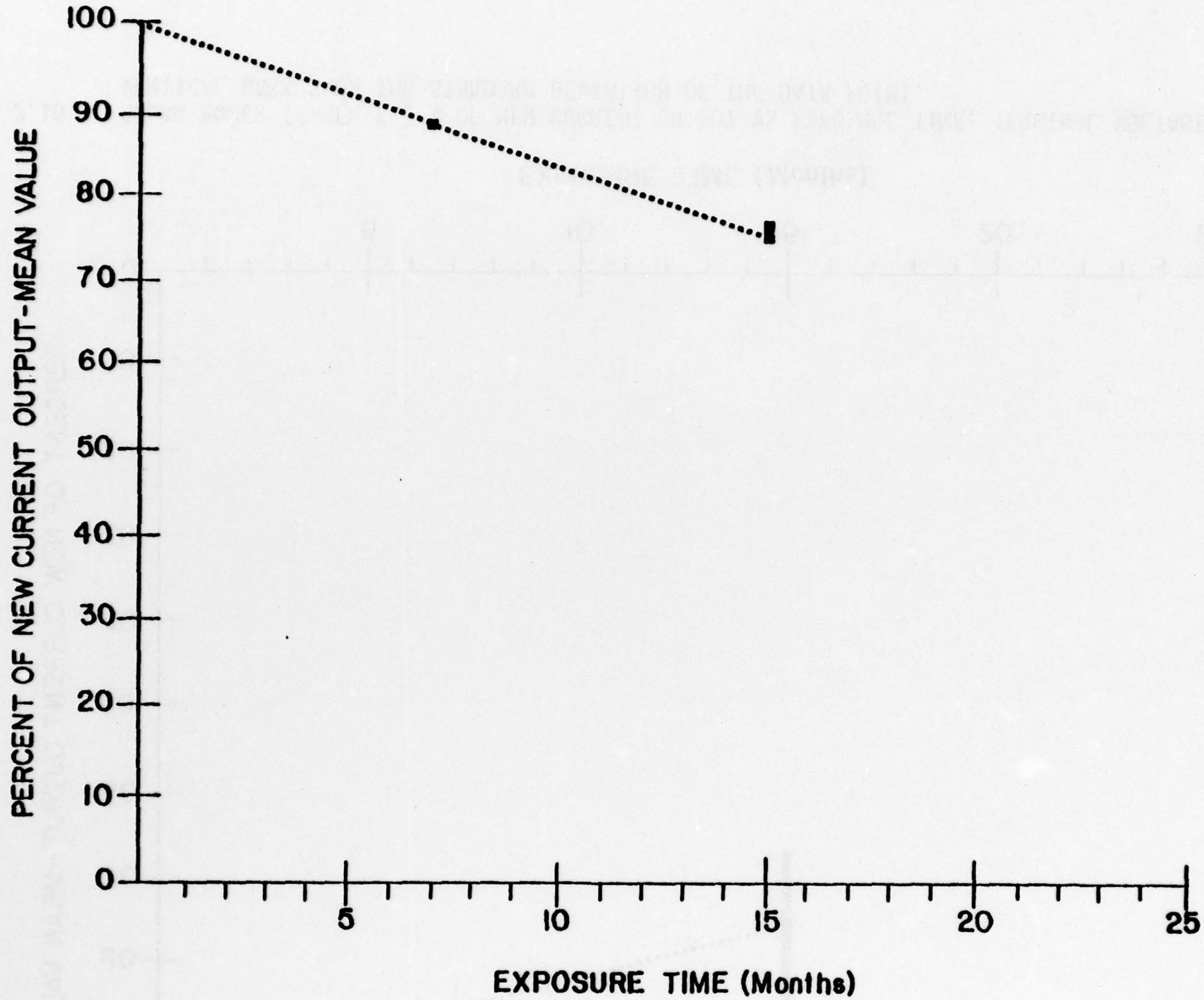

FIGURE 2.9. SOLAR POWER (E-SERIES) % OF NEW CURRENT OUTPUT VS EXPOSURE TIME; TERMINAL VOLTAGE 0.0V. VERTICAL BARS SHOW THE STANDARD DEVIATION OF THE DATA POINT.

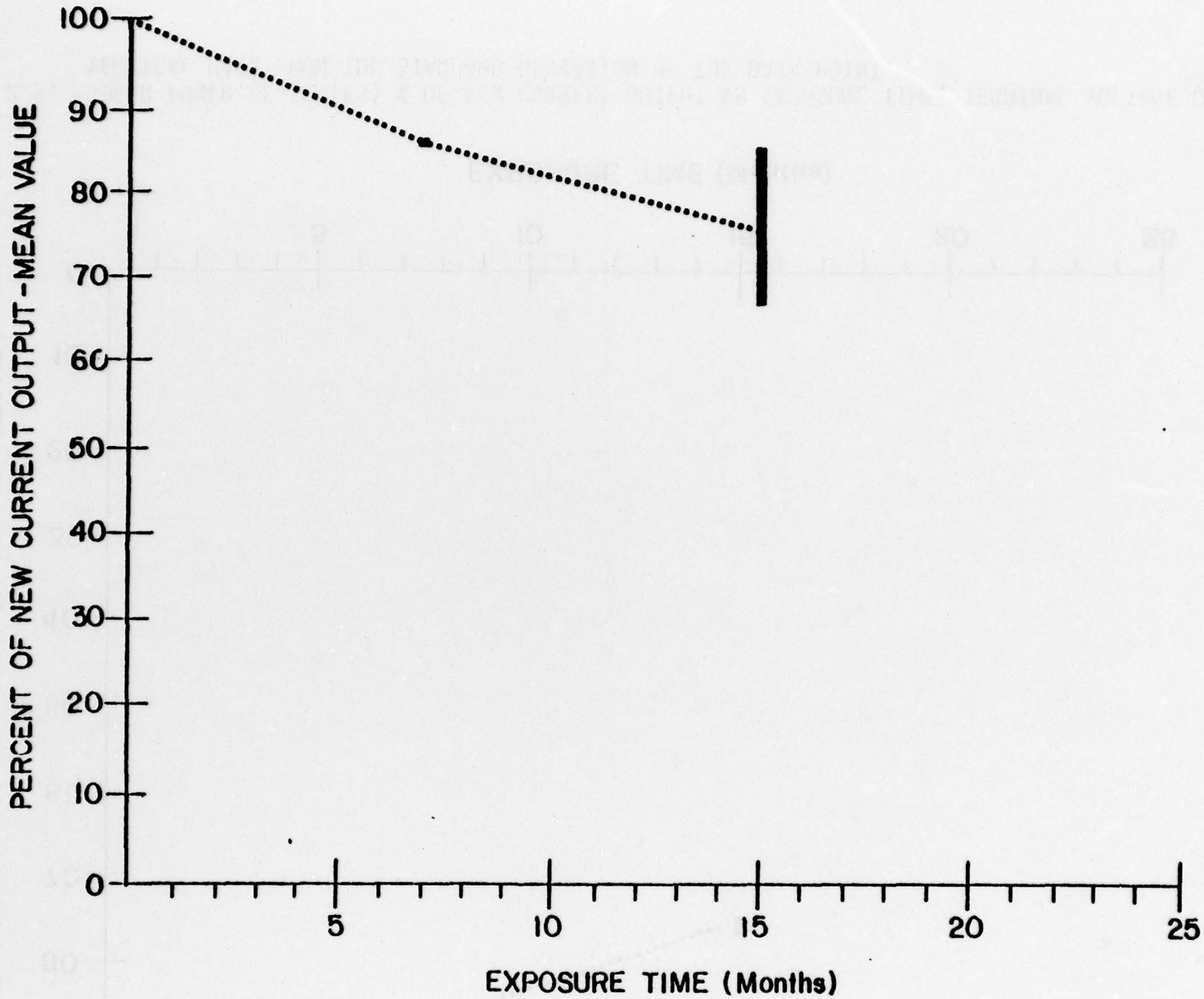

FIGURE 2.10. SOLAR POWER (E-SERIES) % OF NEW CURRENT OUTPUT VS EXPOSURE TIME; TERMINAL VOLTAGE 13.5V. VERTICAL BARS SHOW THE STANDARD DEVIATION OF THE DATA POINT.

3.0 FIELD DEPLOYMENT OF ARRAYS TO KETCHIKAN, ALASKA; ST. PETERSBURG, FLORIDA; AND BOSTON, MASSACHUSETTS:

The objective of this deployment was to demonstrate that solar photovoltaic arrays could successfully function as energy sources for lighted buoys. The deployment arrangement used is described in Table 3.1.

The systems were equipped with coulometers to record the total charge delivered to the batteries. However, periodic readings were not taken because of the "demonstrative" rather than "test and evaluation" nature of this operation.

The buoy used at Ketchikan sunk after it was struck by a vessel after one year of operation. The solar photovoltaic arrays from Boston and St. Petersburg were still functioning at the end of the less than three-year demonstration and were subsequently placed into operation on the rooftop test facility. (The data collected from these panels on the rooftop is not averaged with the other rooftop test data covered elsewhere in this report.)

Quantified results of array performance is not available because of inadequate data collection.

TABLE 3.1

DEPLOYMENT ARRANGEMENT FOR SOLAR-POWERED BUOY DEMONSTRATION

LOCATION	# OF PANELS	MANUFACTURER/WATTAGE	START DATE	END DATE
Ketchikan, Alaska	2	Spectrolab/8W Model LECA PN060015	Mar 1974	Mar 1975
Boston, Massachusetts	1	OCLI/8W Model D-805457	Nov 1973	Sep 1976
St. Petersberg, Florida	1	OCLI/8W Model D-805457	Feb 1974	Sep 1976

4.0 FIELD DEPLOYMENT OF SOLAR PHOTOVOLTAIC ARRAYS ON BUOYS IN LONG ISLAND SOUND:

Two Spectrolab Model LECA PN060015 and six OCLI D-805457 solar photovoltaic arrays were deployed on eight 6X20L (1942-type) buoys on Long Island Sound in the waters surrounding Avery Point, Groton, Connecticut. The objective of this deployment was to compare the operation of solar powered energy systems operating on buoys to those operating on the rooftop facility. The deployment began in June 1974 and terminated in October 1976.

Specific measurements on array output were not collected during this deployment. When this 28-month deployment was concluded, the arrays were placed into operation on the rooftop facility. (The data collected from these panels on the rooftop was not averaged with other rooftop test data covered elsewhere in this report.)

5.0 DEVELOPMENT OF AN ARRAY SCREENING TEST:

The objectives of this task were to (1) develop a solar photovoltaic array performance test and (2) relate, if possible, trends of array degradation in the natural environment to array degradation occurring in the performance test.

A series of controlled environmental tests were performed to attempt to isolate mechanisms which have significant degrading effects on solar modules (modules are array sub-units). Vibration, shock, temperature, salt spray, salt water immersion, and humidity/moisture resistance tests were performed on modules manufactured by OCLI, Spectrolab, Solar Power, and Solarex. These tests did not cause the modules to fail but did introduce failure symptoms. It was decided to combine cycles of salt water immersion, high and low temperature changes, and pressure variation into one test sequence.

A prototype test chamber was built which incorporated these stress elements and which functioned automatically. Initial testing in this chamber resulted in some modules failing, and others deteriorating but surviving. Encouraged by these results, a more refined test chamber was built which allowed entire arrays or single modules to be tested. This refined chamber is still under development.

Initial tests were carried out in which: (1) 55^{o}C salt water was pumped into a tank containing the arrays, (2) air pressurization of the tank to 5 psi was made, for 5 repetitions, and (3) the hot water was removed and 5^{o}C salt water was pumped into the tank and the air pressure increased once to 5 psi. This cycle required one half-hour to complete and was repeated 2281 times for each array tested. I-V characteristics for test panels with 100 mw/cm^2 irradiance at 25^{o}C are given in Figures 5.2 through 5.7. A summary of array performance after testing is given in Table 5.1.

An insufficient number of arrays were examined to provide meaningful statistical information on the degradation of different array constructions. OCLI (Group A), Solarex (Group D), and Solar Power (Group G) groups had sample sizes greater than 1. These groups were subjected to the hypotheses (1) that their degradations, and (2) that their end efficiencies were the same. The hypothesis that the degradations were the same was not rejected at the 95% C.L. The hypothesis that the end efficiencies were the same was rejected only when comparing the G and D groups. That is, the end efficiency of Group G was significantly better than that of Group D. The end efficiency of Group A could not be significantly differentiated from either Group G or Group D.

Clearly more samples must be tested to draw more meaningful results.

TABLE 5.1

SUMMARY OF PIT TESTS

Module Number	Mfg.	Group	Degradation[1]	End Efficiency[2]	Comments
OC2062	OCLI	A	2.4	11.8	Leak in gasket toward end of test
SB8110	Spectrolab	B	96.5	.4	Delamination occurred until complete electrical failure
SP24208	Solar Power	C	21.6	7.2	
SX2464	Solarex	D	14.6	4.6	Loss in fill factor
SB06081	Spectrolab	E	18.5	10.9	
OC2049	OCLI	A	3.4	11.1	Leak in gasket at start of corrosion
SP20398	Solar Power	F	3.5	8.8	
SX3178	Solarex	D	31.8	6.2	Loss in fill factor
OC2065	OCLI	A	100.0	0.0	Leak in gasket immediately after start of test. At 1709 cycles glass exploded causing complete failure
SP0342	Solar Power	G	4.3	11.7	
SX2808	Solarex	D	40.1	3.6	At 1709 cycles Terminal lead corroded off
SP0223	Solar Power	H	6.1	8.7	
ST0010	Sensor Tech	I	2.0	10.9	Delamination of glass cover causing corrosion of cells to start
SP20182	Solar Power	G	6.4	10.3	

Note 1: Degradation = $\frac{\text{max power at end of test}}{\text{max power at beginning of test}} \times 100$

Note 2: End efficiency = $\frac{\text{max power}}{\text{power irradiated}} \times 100$

CONSTRUCTION:

A. Aluminum frame 6 1/2" x 6 1/2" with glass cover sealed with rubber gasket. 36 cells in series-parallel. Potted in RTV 615 with 2 protruding terminal lugs.

B. I-Beam Frame. 18 cells in series potted in R-4 over fiberglass cloth.

C. 5 cells in series on P.C. Board with lexan covering and sylgard potting on back of P.C. Board.

D. 32 cells in series on P.C. Board. Cells potted in material similar to R-4 2 terminal wire leads at one end protruding out of conformal coat with small P.C. Board cover over leads.

E. I-Beam Frame, 20 cells in series potted in R-4 over fiberglass cloth with glass covering.

F. 36 cells in series potted in R-4 on P.C. Board with terminal lugs potted in a small box under board with cable lead protruding out of the box.

G. Same as F but 18 cells in series.

H. 18 cells in series potted in R-4 on fiberglass board with lexan cover same terminal box as in F.

I. 18 cells in series, double connections between cells. Potted on aluminum heat sink type back with safety glass covering, 2 small terminal boards mounted on back.

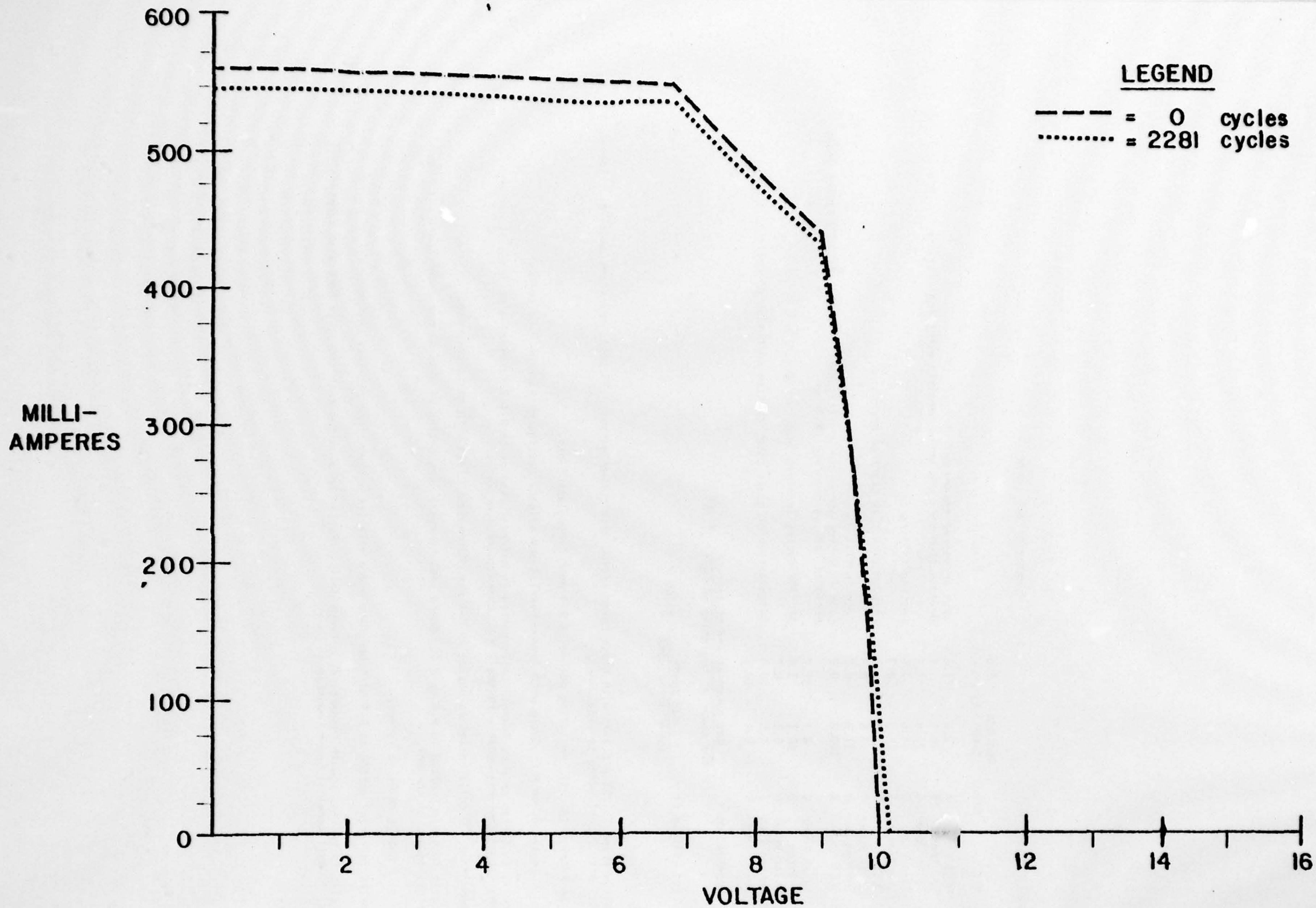

FIGURE 5.2. Current vs Voltage Plot for Sensor Tech Array No: ST0010 prior to and after 2281 cycles of Pit Test.

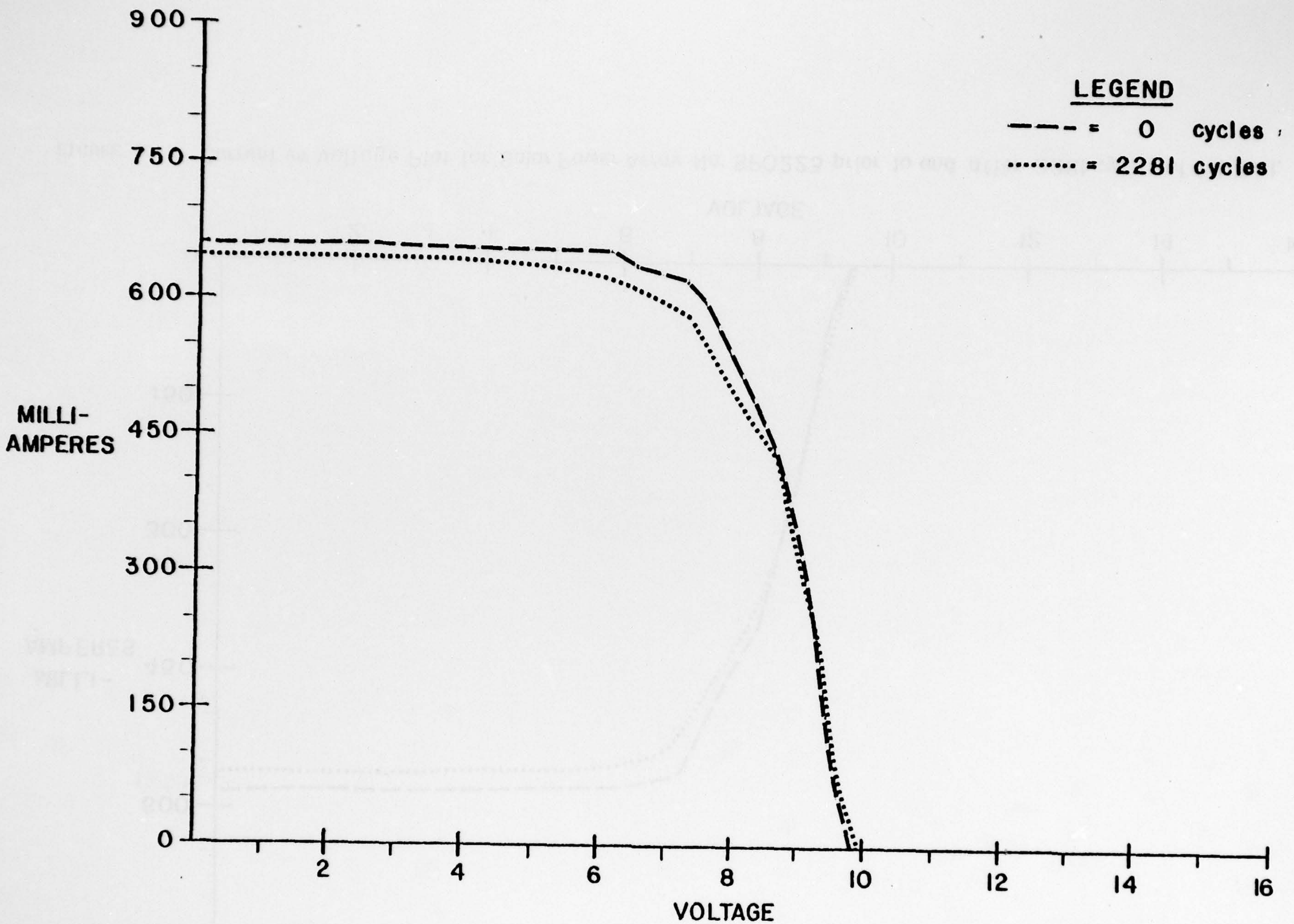

FIGURE 5.3. Current vs Voltage Plot for Solar Power Array No: SP20182 prior to and after 2281 cycles of Pit Test.

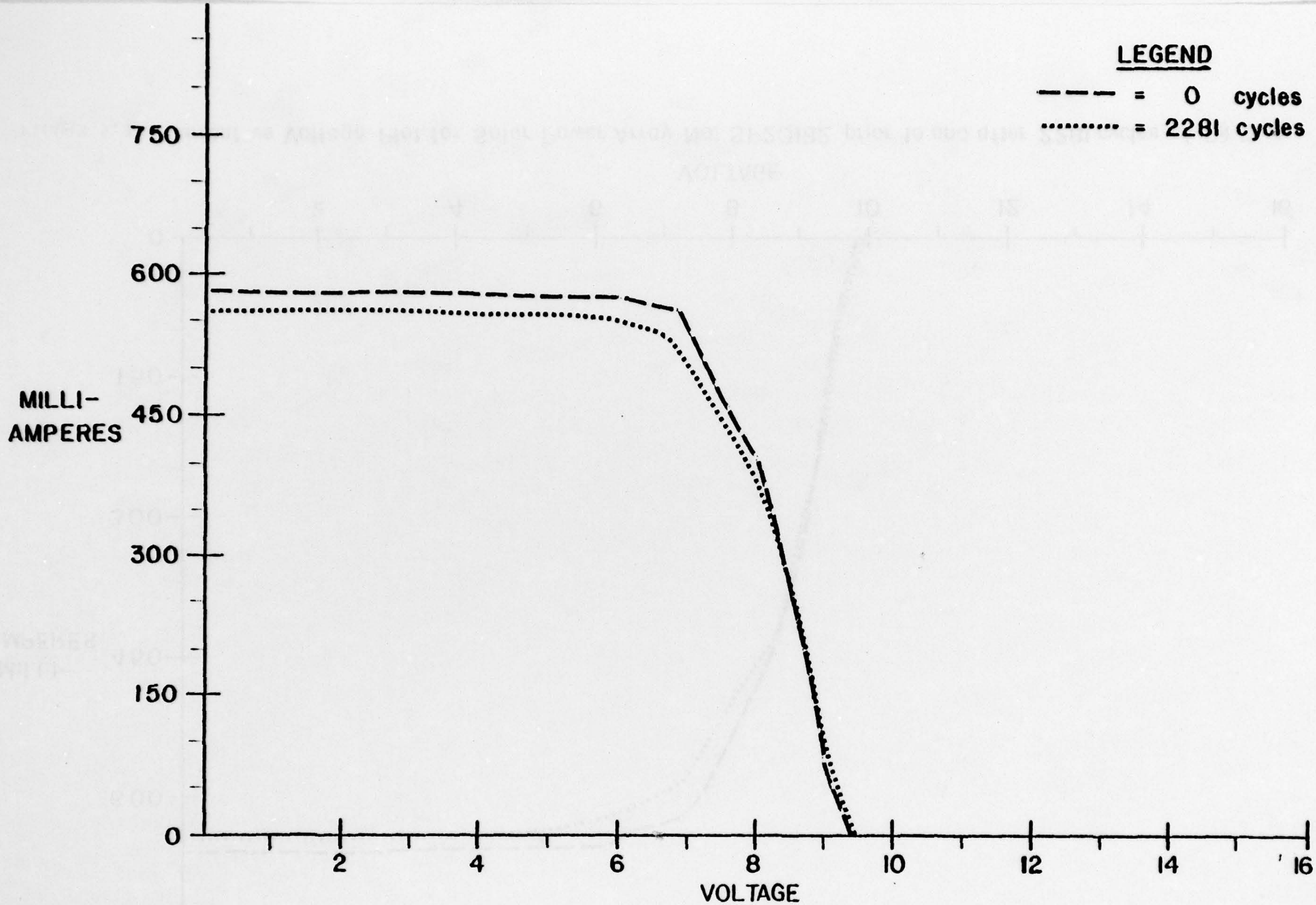

FIGURE 5.4. Current vs Voltage Plot for Solar Power Array No: SPO223 prior to and after 2281 cycles of Pit Test.

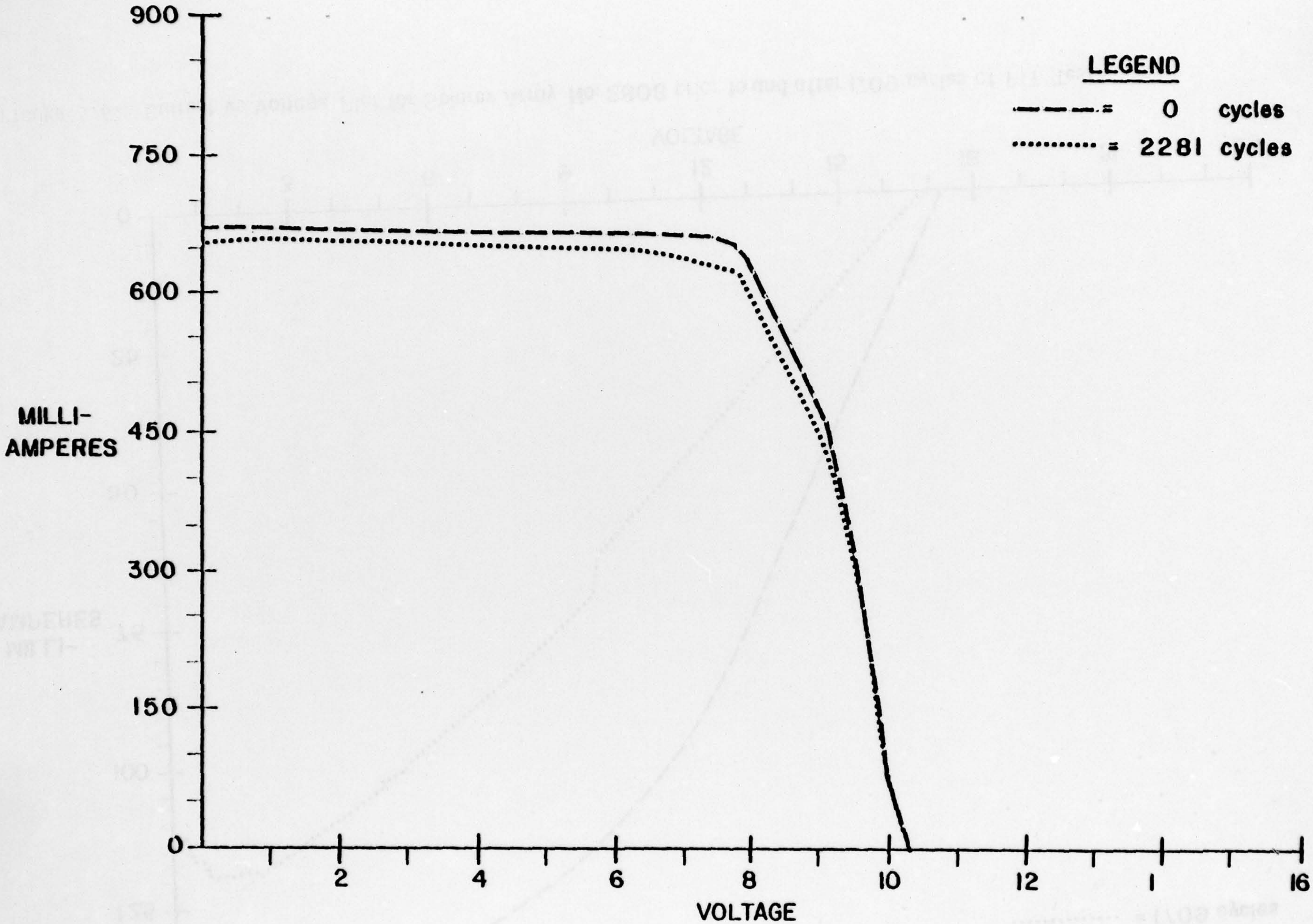

FIGURE 5.5. Current vs Voltage Plot for Solar Power Array No: SP0342 prior to and after 2281 cycles of Pit Test.

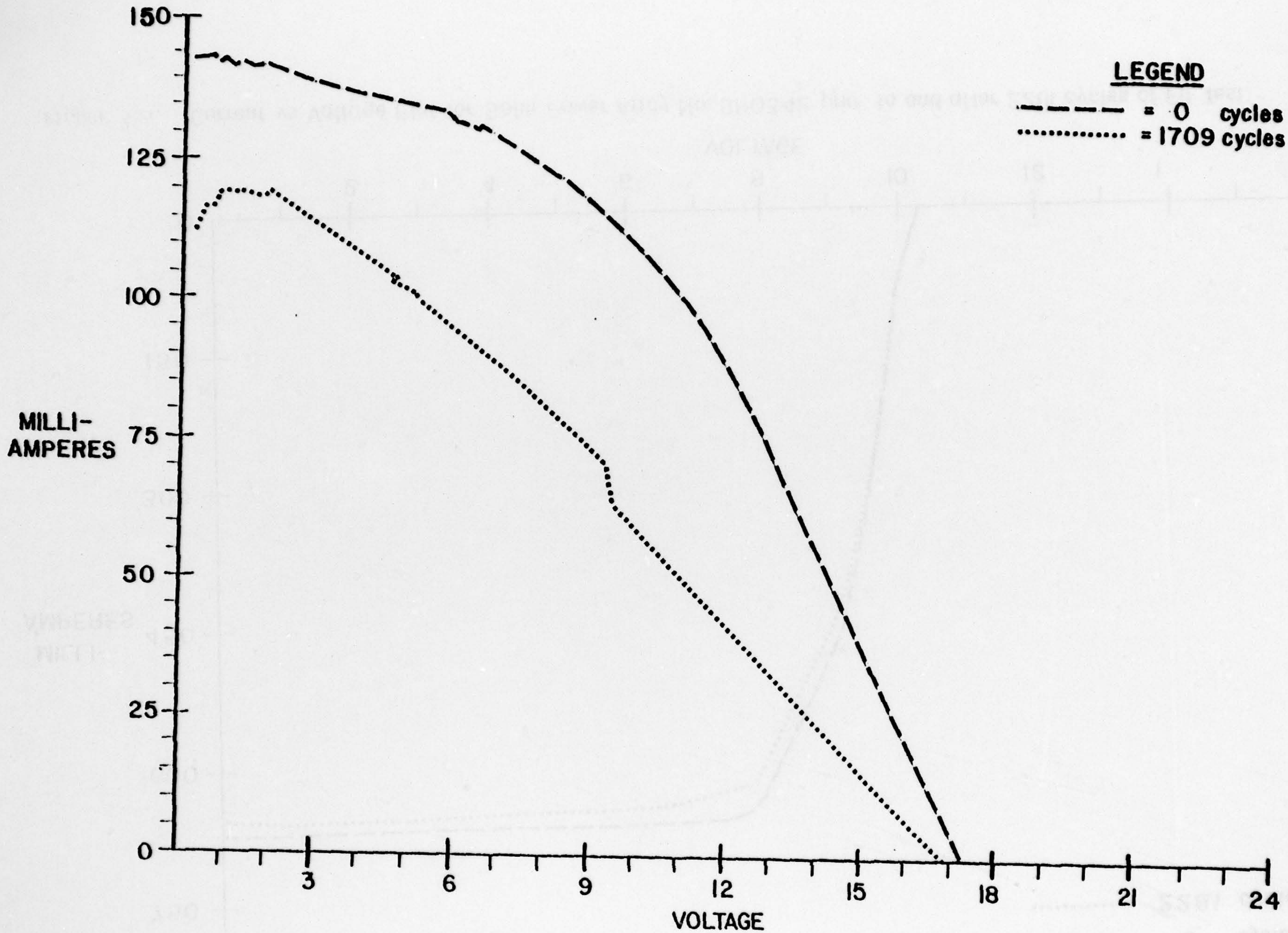

FIGURE 5.6. Current vs Voltage Plot for Solarex Array No: 2808 prior to and after 1709 cycles of PIT Test.

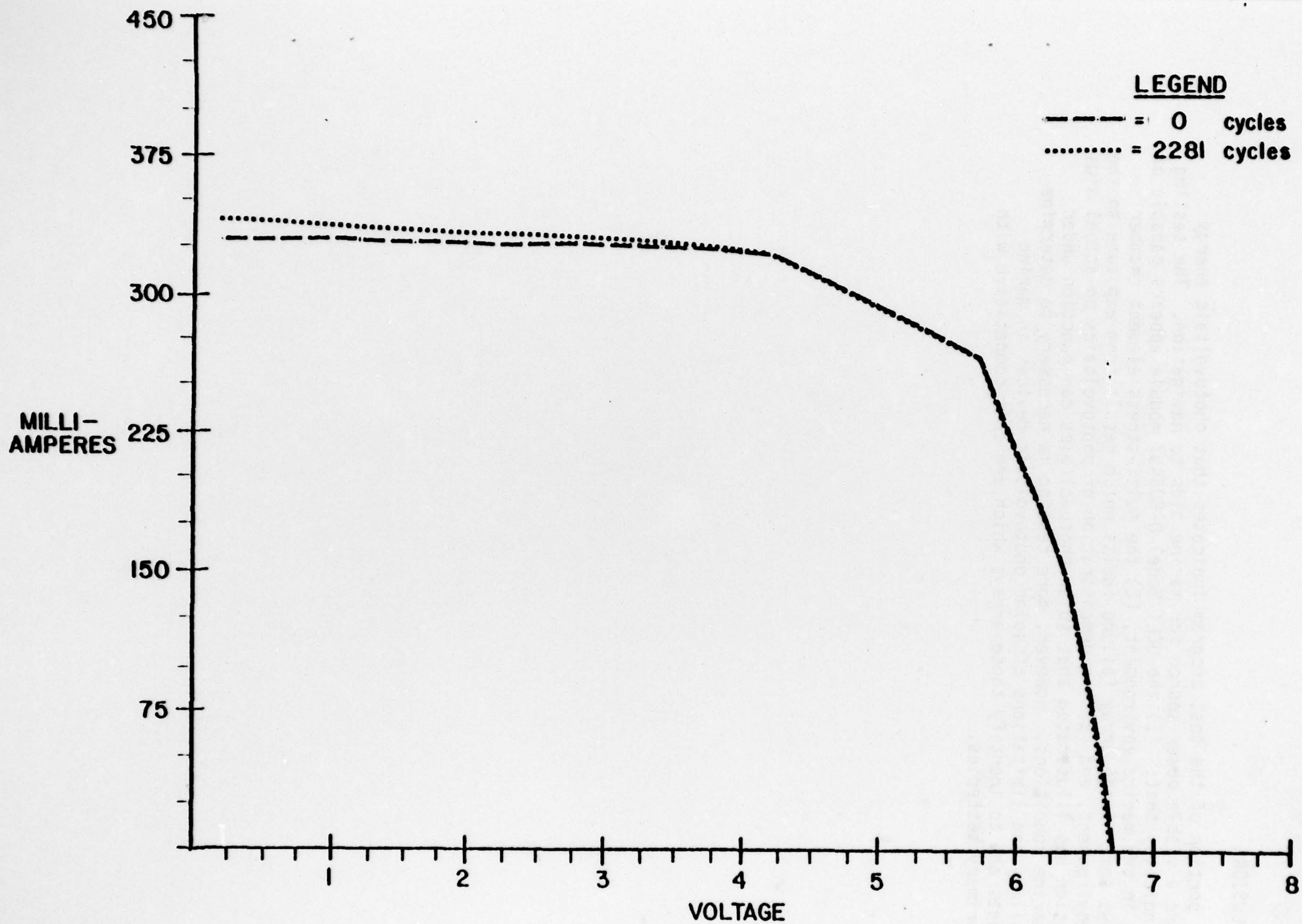

FIGURE 5.7. Current vs Voltage Plot for OCLI Array No: 2065 prior to and after 1709 cycles of PIT Test.

6.0 CONCLUSIONS

This portion of the test program indicates that photovoltaic energy sources are a viable power source for marine aids to navigation. The testing to date indicates that: (1) the OCLI Model D-805457 module appears capable of surviving in the marine environment, (2) the multi-stress element chamber tests shows some of the array failure faults which result from exposure to the natural environment, and (3) the demonstration of photovoltaics on actual aids to navigation has illustrated that solar photovoltaics can function under various marine conditions. However, more testing is necessary to determine the capability and limitations of solar photovoltaic devices in marine environments and to identify those arrays which are cost competitive with today's primary batteries.